Overview of NRL's maritime laser communication test facility

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ABSTRACT

NRL has established a 20 mile round trip laser communication test facility across the Chesapeake Bay for investigating lasercomm performance in a maritime environment. Experiments at this facility have successfully demonstrated links at data rates up to 2.5 Gbps and at lower rates in light rain and fog. This facility is currently being upgraded to allow long term monitoring of a one-way 10 mile link across the Bay. Parameters monitored will include BER, turbulence conditions, atmospheric transmission, and meteorological conditions. A summary of past results, the design/status of the upgrade to the test facility, and recent results will be presented.

Keywords: Lasercomm, free-space optical communications, scintillation, atmospheric turbulence

1. INTRODUCTION

As information has become an increasingly important resource on the battlefield, the DOD has been experiencing more and more communications bottlenecks. Recently, with the increasing maturity of its components, lasercomm has emerged as a viable approach for high-speed free space LOS communications. Previous experiments by NRL[1,2,3] over a 32 km path over the Chesapeake Bay have shown that long range maritime lasercomm links are feasible in a wide range of atmospheric conditions (see Figure 1). Lasercomm links can operate at 10's of gigabits per second with no frequency allocation or mutual interference issues. This is because the intrinsic bandwidth of lasers is very high (~petahertz) and because the directionality of lasercomm systems (typically < 1 milliradian) makes mutual interference extremely unlikely. High directionality and speed also make lasercomm systems have extremely low probabilities of intercept and detection since power is radiated only in very specific directions and high speed burst communications can be used to minimize transmission times. Additionally, lack of RF radiation allows operation of lasercomm systems in conditions when RF communications are not advisable. A typical ship-to-ship lasercomm transceiver would be small (~2 ft^3), lightweight (~30 lbs), and consume relatively low power (~100 watts). These qualities of a lasercomm system make lasercomm highly desirable for Naval communications.

However, lasercomm is disrupted by substantial fog, heavy rain, snow, heavy atmospheric turbulence, and, as a result, is not all weather. In addition, lasercomm requires direct LOS between terminals and is therefore limited in range (~35 km range between two terminals on 30 meter ship masts). A hybrid lasercomm/RF system is therefore the most likely implementation of a future communication system with high bandwidth lasercomm used when possible and lower data rate RF used as a backup. This system would allow battle groups to greatly increase data rates and reduce or eliminate RF communications a majority of the time. The percentage of time this would be possible and the technologies and techniques to maximize this time are a central goal of NRL's research program.

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14. ABSTRACT

NRL has established a 20 mile round trip laser communication test facility across the Chesapeake Bay for investigating lasercomm performance in a maritime environment. Experiments at this facility have successfully demonstrated links at data rates up to 2.5 Gbps and at lower rates in light rain and fog. This facility is currently being upgraded to allow long term monitoring of a one-way 10 mile link across the Bay. Parameters monitored will include BER, turbulence conditions, atmospheric transmission, and meteorological conditions. A summary of past results, the design/status of the upgrade to the test facility, and recent results will be presented.

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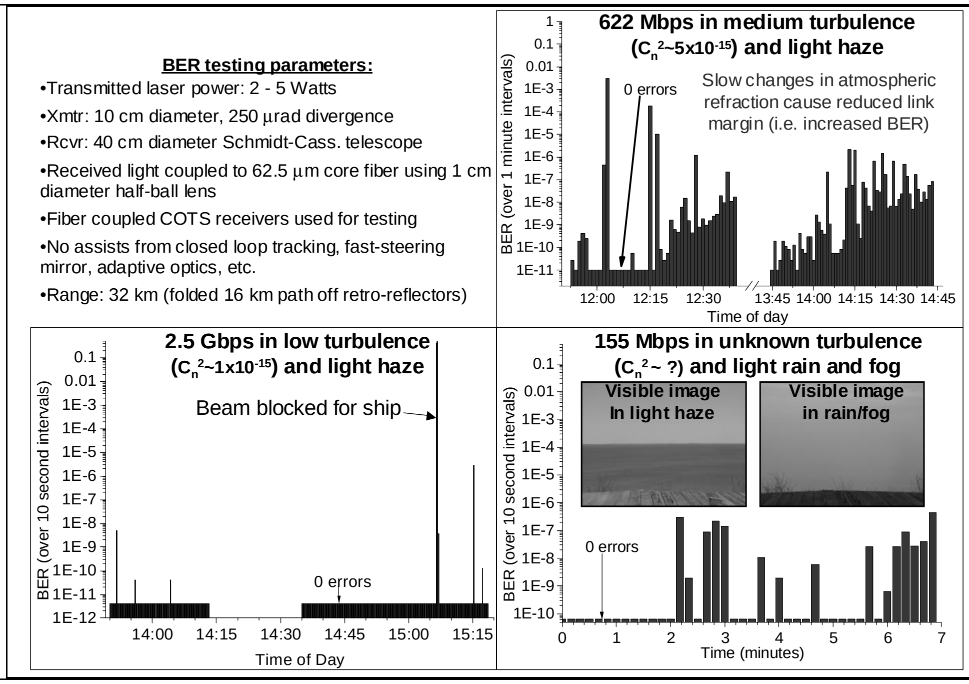

Figure 1: Maritime bit-error rate testing over 32 km maritime test range at NRL's Chesapeake Bay Detachment

2. NRL'S LASER COMMUNICATION TEST FACILITY (LCTF)

A central goal of our research effort is long term monitoring of lasercomm performance and implementation of new receivers and techniques at the test facility. NRL's lasercomm test facility (LCTF) consists of a building on a cliff 30 meters above the water on the western shore of the Bay at NRL's Chesapeake Bay Detachment (NRL-CBD), and a small area of land located on the eastern shore at approximately water level (NRL-Tilghman Island). Over the last few years, an array of twelve retro-reflectors situated 15 meters above water level at NRL-Tilghman Island has been used to "fold" the path of a lasercomm system to allow testing from NRL-CBD with minimal activities at NRL-Tilghman Island (Figure 2). This folded 32 km path has been used intermittently to gather samples of lasercomm performance and atmospheric conditions over short durations. Intermittent sampling has shown successful closure of maritime lasercomm links at rates from 155 Mbps to 2.5 Gbps and some general understanding of the turbulence conditions over a 16 km maritime path. Recently, these twelve retro-reflectors were replaced with an array of 25 new two inch retro-reflectors. The new BER results presented in this manuscript in section 5 were obtained using this new array of 25 retro-reflectors.

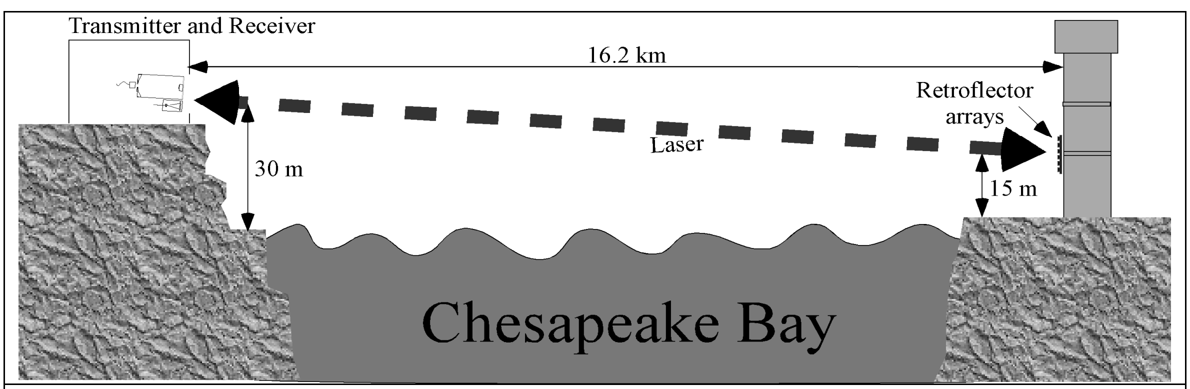

Figure 2: 32 km retro-reflected lasercomm test range between NRL-CBD and NRL-Tilghman Island

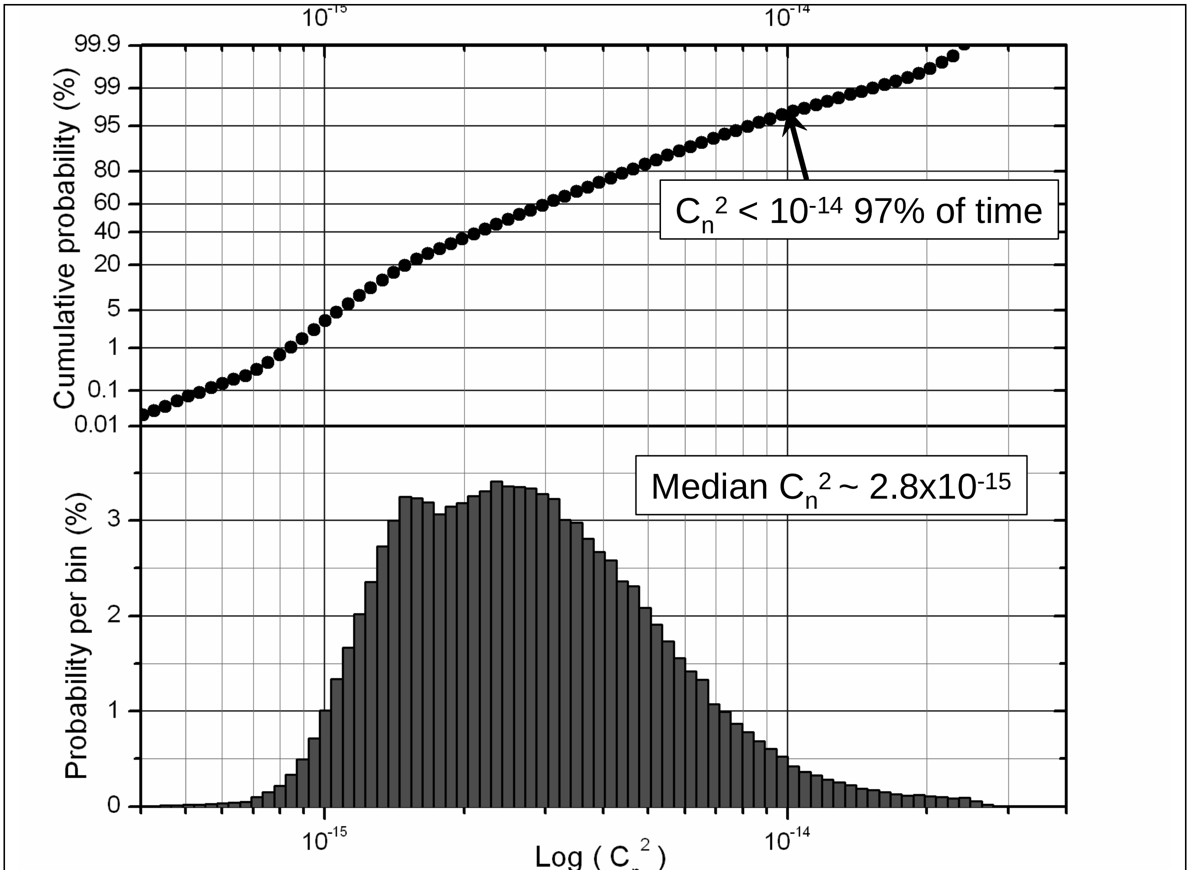

Figure 3: Histogram (bottom) and cumulative probability (top) of C_n^2 values measured over the Chesapeake Bay using the passive AOA turbulence monitor from May 17th to July 11th 2005.

Atmospheric turbulence measurements at the NRL-LCTF have been performed using a passive optical monitor based on measuring angle-of-arrival (AOA) fluctuations of an incoherent source. This turbulence monitor has been described in detail elsewhere.[4,5] A specific example of turbulence conditions observed from May 17th to July 11th in 2005 is shown in Figure 3. This figure shows a histogram of the index of refraction structure constant (C_n^2) estimated from AOA measurements (bottom) and a cumulative sum of the histogram normalized to show the cumulative probability (top). Apparent from this figure is that C_n^2 was below 10^{-14} $m^{-2/3}$ 97% of the time and was typically 1-5x10^{-15} $m^{-2/3}$ (median $C_n^2 = 2.7x10^{-15}$).

In addition to the fast time scale AOA fluctuations caused by turbulence over the test range, there are also slow time scale pointing changes caused by large scale temperature gradients over the bay.[6] These gradients mainly cause refraction in the vertical direction and are caused by the relative temperature of the water to the air and the amount of mixing caused by the wind. During a great majority of the time (>>90%), the gradients over the Bay are relatively continuous and have only a minor effect on the beam (~10's of microradian/hour pointing changes). However, in rare instances, conditions are right to generate large rapid pointing changes (up to 1 milliradian/minute) and vertical beam breakup into multiple spots. In these conditions, stagnant non-continuous layers of various temperatures settle over the Bay and cause rapid pointing changes as different temperature layers rise/lower through the beam. These conditions also cause mirages resulting in distortion and/or reflections of objects on the opposite side of the Bay. Results of experiments investigating this effect on the laser beam are presented in reference 7.

3. CURRENT STATUS OF THE LCTF

The LCTF is currently being upgraded to a one-way automated link to better simulate ship-to-ship lasercomm and allow long term monitoring of link performance versus atmospheric conditions (see Figure 4). The conversion to a one-way link requires construction of a concrete pad on Tilghman Island and placement of an existing trailer on this pad for housing of the lasercomm receiver unit and diagnostic equipment. The link will be automated by implementing slow (< 1 Hertz) tracking systems on both the receiver and transmitter to maintain the required alignment between the two (~100 microradians). A slow RF link (~100 kbps) will be used in parallel to the lasercomm link to allow command and control of the Tilghman end of the link from NRL-CBD. Finally, a wide divergence laser (> 1 milliradian) will be propagated from CBD to Tilghman Island and received with a position sensitive detector to allow measurement of atmospheric turbulence strength and transmission.

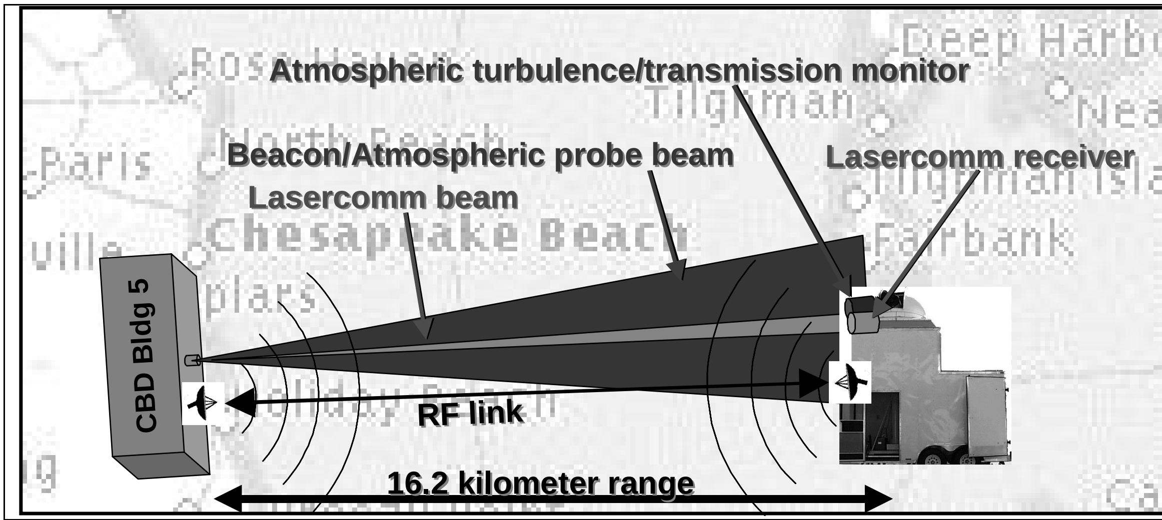

Figure 4: Overview of one-way lasercomm test facility between NRL-CBD and NRL-Tilghman Island

Construction of the one-way lasercomm test facility is underway. A summary of the more important tests, results, etc. are:

-Experiment performed to investigate smaller receiver optics (5-6") and tracking requirements (see detail below)
-All major hardware bought and in house for one-way test facility
-Fiber positioner installed, and successfully tested on lasercomm transmitter at NRL-CBD
-Data acquisition system for tracking system operational at NRL-CBD*
-Position sensitive detector (PSD) and Si/Phosphor CCD installed at NRL-CBD for testing*
-Slow tracking algorithms using Si/Phosphor CCD and PSD sensors under development*
-Concrete pad constructed at Tilghman Island and trailer installed on pad (see Figure 5)
-RF modem successfully tested over CBD-Tilghman link
-O-E-O multimode fiber receiver constructed and tested in various conditions
-Adaptive thresholding testbed constructed to test adaptive thresholding algorithms for future implementation at the LCTF

*These accomplishments are temporary setup of Tilghman Island components at CBD to develop software necessary for tracking system. Hardware/Software will be moved to Tilghman Island during construction of receiver in trailer on Tilghman Island.

Figure 5: Trailer for housing receiver in new one-way lasercomm test bed installed on pad at Tilghman Island

Some of the tests/results listed above are described in detail elsewhere.[7,8,9] One of these tests involved using two co-boresighted receivers – one using a CCD and another using a PSD –on Tilghman Island to measure received power and angle-of-arrival fluctuations of a beam transmitted from NRL-CBD.[7] Testing occurred on March 18th when turbulence conditions were relatively high ($C_n^2 \sim 10^{-14}$ m$^{-2/3}$). One of the most significant/promising results on this day was the received power levels. The median received power level was measured to be on the order of 4 milliwatts and the minimum received power was on the order of 40 microwatts. Considering the significant turbulence present on the day of the test ($C_n^2 \sim 10^{-14}$ m$^{-2/3}$), this is extremely promising for closing even high data rate lasercomm links since COTS 10 Gbps receivers are available (e.g., SU-10ATR from Sensors Unlimited, Inc.) with typical sensitivities of –24 dBm (4 microwatts). This demonstrates that the raw power necessary to close the link is available but work will be required to couple the received power into a small (~10's of microns) high speed detector due to the image dancing present in the focal plane. Another test was done using a germanium PSD to measure slow AOA changes over the 32 km link and track these changes with a fiber positioner located in the transmitter. Details of this experiment are given in reference 8. Testing has also been performed on adaptive threshold detection for improved link performance at the LCTF. Details of this experiment are given in reference 9.

4. OC48 MULTIMODE FIBER O-E-O RECEIVER

Although atmospheric turbulence averaged over the path at the LCTF is relatively low, angle of arrival fluctuations of the received laser beam cause the effective focused spot size to be much too large to efficiently couple into a single mode fiber. Since the majority of commercially available high speed telecom optical receivers are fiber coupled with single mode fibers, FSO receivers must be special ordered with multimode fibers or with no fiber coupling. The majority of our FSO efforts have used laser wavelengths of 1550nm to take advantage of the development done by fiber telecom companies, as well as to take advantage of the much higher flux levels allowed while still being below the minimum permissible exposure (MPE) for eye safety. NRL's Optical Sciences Division has developed an OC48 multimode fiber O-E-O receiver using these COTS components.

A block diagram of the OC-48 O-E-O converter is shown in Figure 6. It is constructed with COTS components from several different manufacturers. The optical receiver is a Fujitsu receiver, model FRM5W231DR, InGaAs APD with transimpedance amplifier (TIA). The detector has a 30 μm diameter active area, and is coupled to a 62.5-micron core multimode fiber. It has a 2.5 Gbps data rate (2.0 GHz

BW) and a sensitivity of 1.0 A/W at 1550nm. The TIA has a transimpedance of 600 ohms. The receiver is in a butterfly PC board mount package and has noise current density of 6.5 pA/rtHz and rated sensitivity of –34 dBm for 10^{-10} BER. The electrical output of the Fujitsu receiver is passed through a Picosecond Pulse Labs, model 5915-100-1.87GHz, low pass filter with a -3dB cut-off at 1.87 GHz, before being applied to a Maxim Semiconductor multirate clock and data recovery chip (CDR). The CDR chip is a model MAX3872 with adjustable rate (OC-3, OC-12, OC-24, and OC-48), adjustable detection threshold, and an integral limiting amplifier. The output of the CDR chip drives an OCP OC-48 optical transmitter module. The transmitter module is an STX-48-HP-LR1 rated at 0 dBm at 1310nm.

The OC-48 O-E-O converter sensitivity was measured in the laboratory for 1550nm and for a BER of 10^{-9}. The sensitivity at OC-48 was between -33 and -34 dBm. The sensitivity at OC-3 and at OC-12 was –37 dBm.

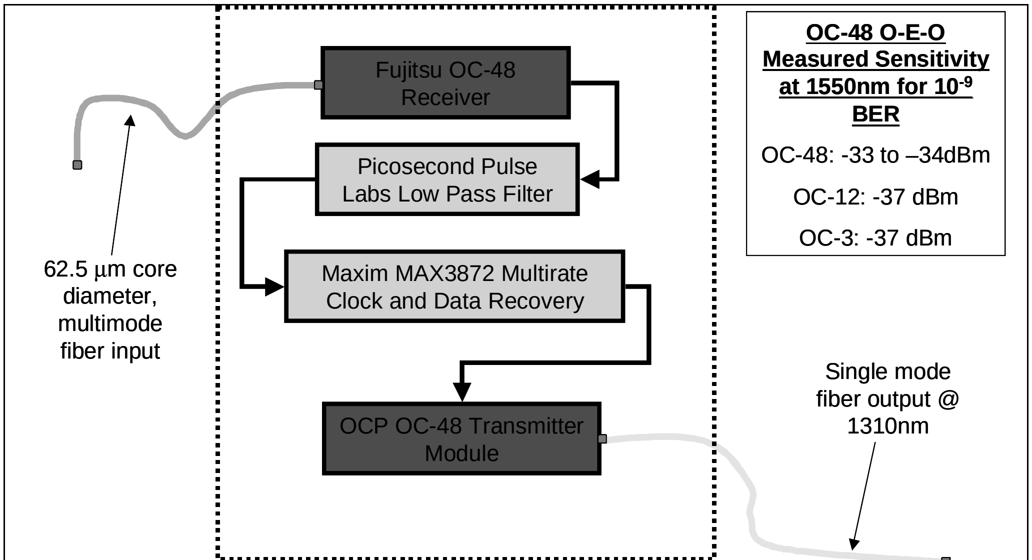

Figure 6. OC-48 O-E-O Block Diagram.

5. BER TESTING

BER testing at various rates and under various weather conditions have been performed for several years at the NRL LCTF with no assists from closed loop tracking, fast-steering mirrors, adaptive optics, or forward error correction coding. Many of the results have been previously reported[1-3]. Recently, with the construction of the multi-mode fiber O-E-O receiver, we have begun OC-48 testing in various conditions over our 32 km folded path test range. Initial testing with this O-E-O receiver is described in reference 3. Typical operating conditions used during BER testing at the LCTF are: transmitted laser power = 2 - 5 Watts; wavelength = 1550 nm nominally (C band, 1535 – 1565nm); 32.4 km roundtrip off of an array of twenty-five two-inch retroreflectors on the tower at Tilghman Island; receive light coupled to 62.5 micron core diameter multimode fiber using 10-mm diameter half-ball lens; fiber coupled receivers used for all testing.

OC-48 (2.5 Gbps) Bit-error-rate testing has been performed with the new OEO receiver module using multiple setups under a few different configurations. All testing was performed over the 32 km folded path test range. The first testing was performed using the bi-static transceiver we have used for all previous testing. The lasercomm transmitter shown in Figure 7 and the receiver shown in Figure 8 are arranged in a bi-static configuration with a 40 cm separation of their respective axes. The transmitter beam is modulated with an OC-48 pseudo-random bit sequence from an Agilent 86130A BER tester, amplified in a Keopsis EDFA (maximum P_{out}=5 Watts), and transmitted with a beam diameter of approximately 100 microradians through a standard glass window to reduce the effects of thermals rising through the window. These thermals have been seen to cause large scale beam wander and a corresponding increase in

scintillation in previous experiments. The receiver is a 16-inch Meade telescope mounted in an Az-El gimbal. The Meade has an effective focal length of 4 meters, and its output is coupled into a 62.5 micron core multimode fiber using a short focal length half-ball lens. The multimode fiber provides the input to the new OC-48 O-E-O converter. The O-E-O converter provides sensitive detection and compatibility with optical fiber networks and test equipment. For BER testing, the single mode fiber output of the O-E-O converter is connected to an OC-48 receiver module from OCP for conversion back to electronic before applying the received signal to the error detector of the Agilent 86130A BER tester.

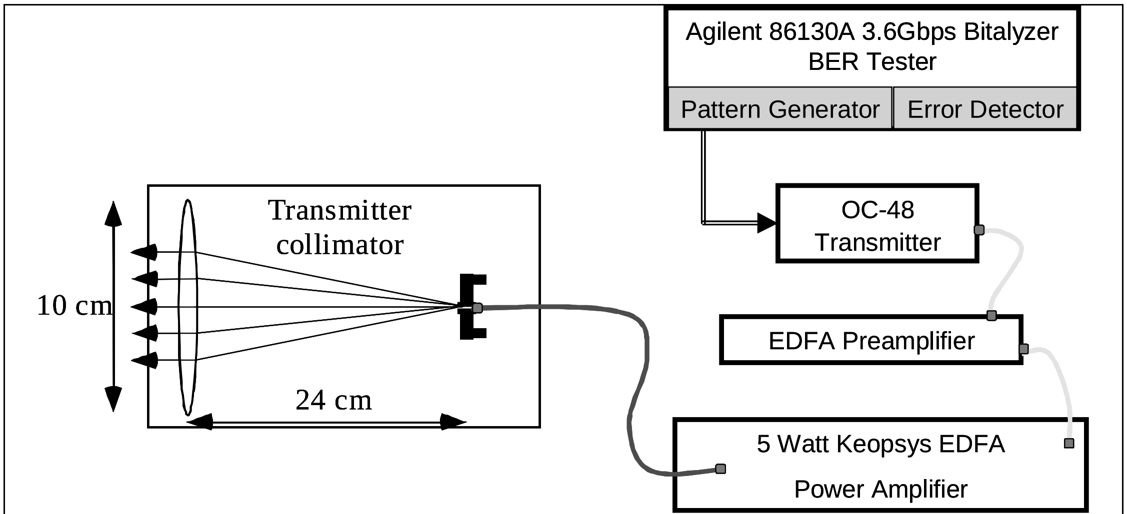

Figure 7. Transmitter configuration for BER testing

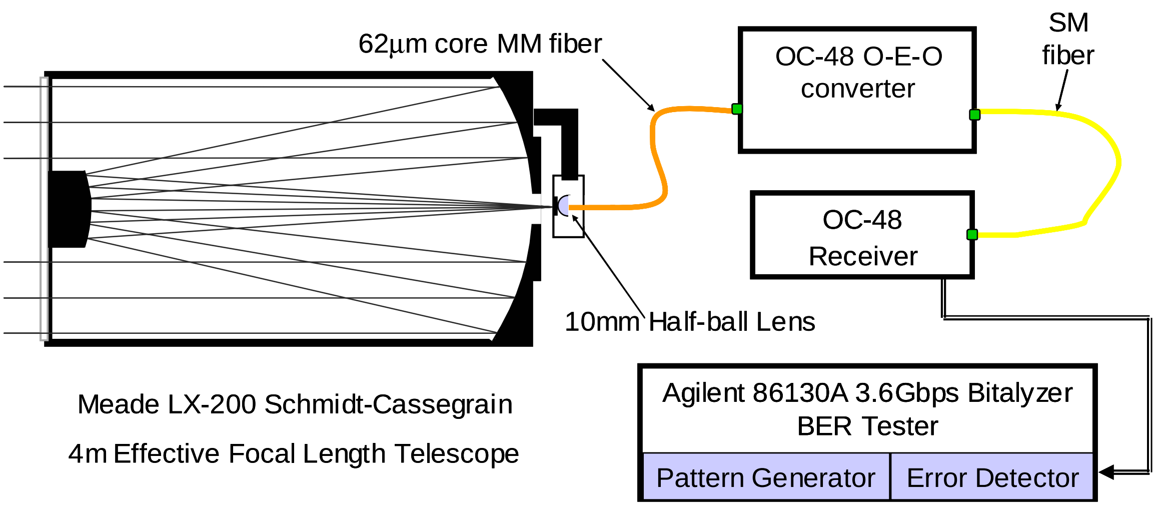

Figure 8. Receiver configuration for BER testing.

The BER data from July 5th is shown in Figure 9. A BER of approximately 6×10^{-13} was imposed on the data to represent zero errors in a time interval. Transmitted laser power was approximately 5 Watts. C_n^2 was approximately $1\text{-}2\times10^{-15}$ during the entire test. The weather was stable with the following characteristics: hazy with visibility < 10 km; temperature ≈ 27° C; humidity ≈ 81%; average wind speed ≈ 8 mph; water temperature ≈ 26° C. All weather parameters except water temperature are measured from a rooftop weather station at NRL-CBD which is approximately 40 m above the water (10 meters above the transmitter/receiver). Water temperature is obtained from the NOAA weather station at Thomas Point Lighthouse approximately 15 miles north of NRL-CBD and Tilghman Island. C_n^2 is measured with the AOA turbulence monitor.

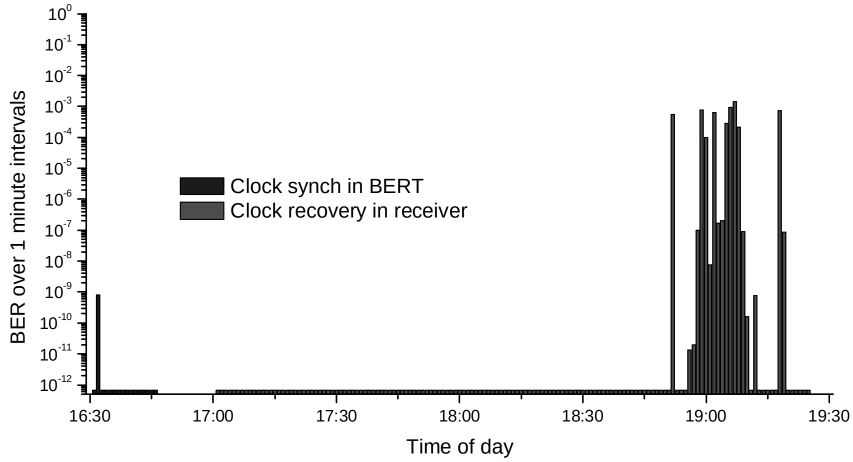

Figure 9: Maritime OC-48 bit-error rate testing on July 5th 2005 over 32 km maritime test range at NRL's Chesapeake Bay Detachment

The first grouping of data from approximately 16:30 to 16:45 was taken with the clock signal directly connected from the output of the BER tester pattern generator to the input of the BER error detector. At the beginning of this fifteen minute interval the average received power was approximately 46 microwatts. The approximately 2½ hours of testing after this was taken with clock recovery performed in the OC-48 OCP receiver. At the beginning of this 2½ hour interval, the average received power was approximately 100 microwatts. This testing showed extremely good performance with only a single interval with errors at 16:33 and no errors until 18:52. At 18:52 and later, substantial errors began to occur indicating the pointing of the system drifted and power levels into the receiver dropped.

A second set of BER data was acquired on July 8th, 2005. This data set was collected as the remnants of Tropical depression Cindy left the NRL-CBD area. During this testing, weather conditions were <u>not</u> stable. A graph showing weather parameters and C_n^2 versus time is shown in Figure 10. Of particular note were the strong winds (15 mph average wind speed with 25 mph gusts) and the high value of C_n^2 (~$7x10^{-15}$) at the beginning of the testing. The results of the OC48 BER testing performed during this weather event are shown in Figure 11. During the initial 30 to 45 minutes of testing, the average received power was 100 microwatts but significant errors were still observed even though the average power was >20 dB above the detection threshold of the O-E-O receiver. Approximately 45 minutes into the test, C_n^2 dropped to approximately $5x10^{-15}$ accompanied by a drop in wind speed of approximately a factor of 2 (15 mph to 7 mph) while the average received power remained approximately 100 microwatts. This combined drop in C_n^2 and wind speed appeared to greatly decrease fading and significantly improve the BER rate. This is most likely due to a two fold improvement due to the decrease in turbulence strength and a decrease in the temporal frequency of the turbulence fluctuations (due to the decreased wind speed). Simultaneous measurement of BER and power is planned for the upgraded LCTF which should allow better characterization of this type of effect. During the next three hours of the test, atmospheric conditions improved and the BER remained excellent – typically no errors with very few excursions above a 10^{-9} BER. The event at approximately 14:05 was likely a bird or similar obstruction passing through the transmitter beam near CBD. Over the duration of this test approximately 3 terabytes were transferred over the 32 km link.

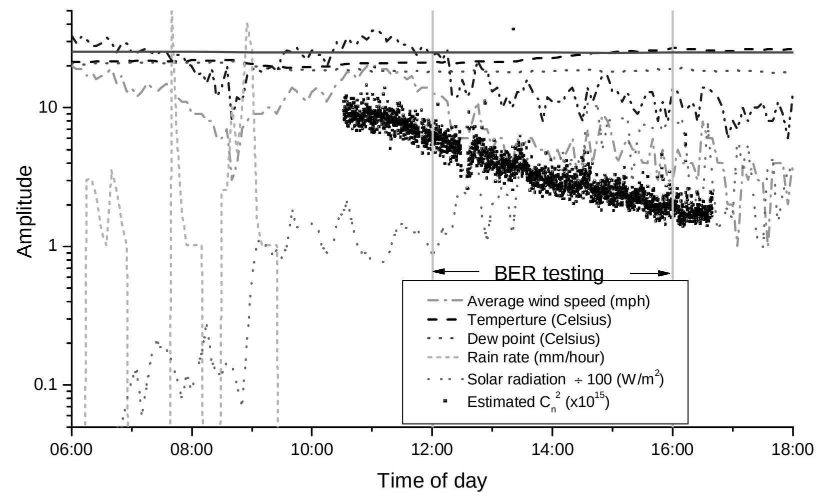

Figure 10: Weather and turbulence data during BER testing on July 8th 2005.

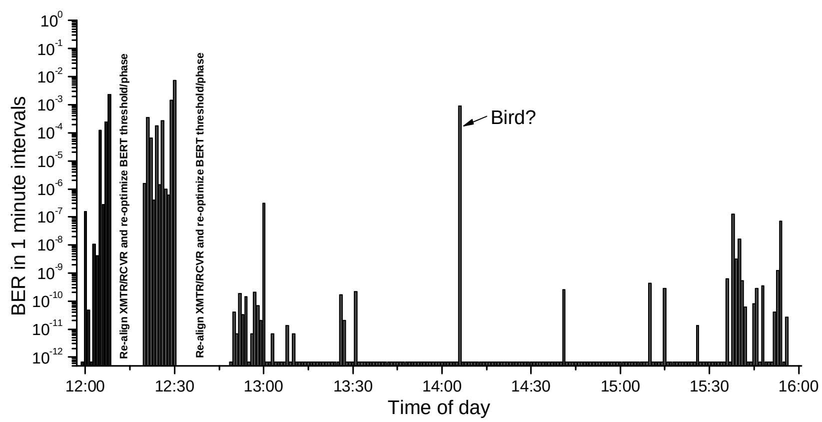

Figure 11: Weather and turbulence data during BER testing on July 8th 2005.

Testing was also performed with a commercial lasercomm transceiver from Novasol Inc. developed under the Dual-mode-optical-interrogator (DMOI) program (see Figure 12). This transceiver is bi-static with 5" transmit and receive lenses separated by approximately 5.5". The transmit and receive paths both contain fast steering mirrors for fine tracking which are both driven by feedback from a quadrant detector in the receive path. The transmitter was fed by a single-mode fiber (SMF) from a Keopsis erbium doped fiber amplifier (EDFA) with a maximum output power of 5 Watts which was seeded by a COTS OCP OC-48 transmitter module. The receiver path coupled received power to a 62.5 micron core multi-mode fiber (MMF) which was detected with the O-E-O receiver described above. The Novasol system was operated through an open window due to problems in the tracking system caused by reflections from the window when closed. This will increase scintillation due to thermals rising through the window as noted above.

Experiments testing the new O-E-O receiver and the DMOI from Novasol were performed over the 32 km folded path test range at the NRL LCTF on June 2nd, 2005. The DMOI was operated in tracking mode throughout the entire test. Results from the testing are shown in Figure 13. Testing was performed over approximately 1¾ hour for various transmitter power levels. During this testing, weather conditions

and turbulence strength were relatively stable with the following characteristics: temperature ≈ 18° C, humidity ≈ 84%, average wind speed ≈ 7 mph from ENE, water temperature ≈ 19° C; and $C_n^2 \sim$ 1-2 x 10^{-15}.

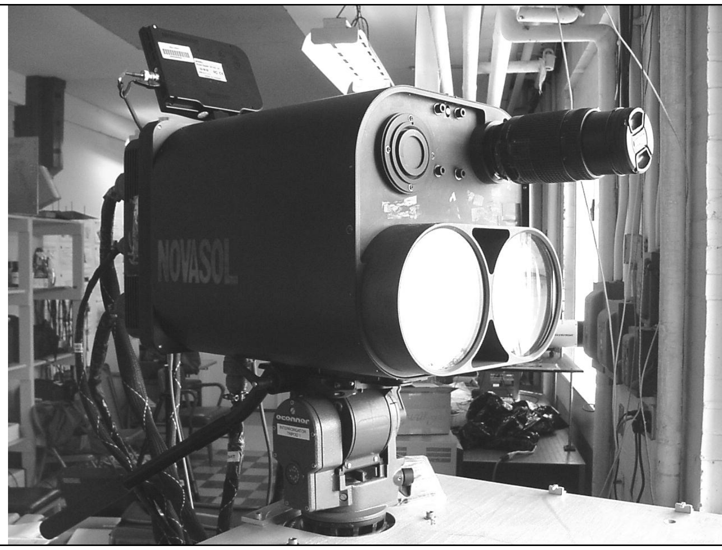

Figure 12: Novasol DMOI lasercomm transceiver

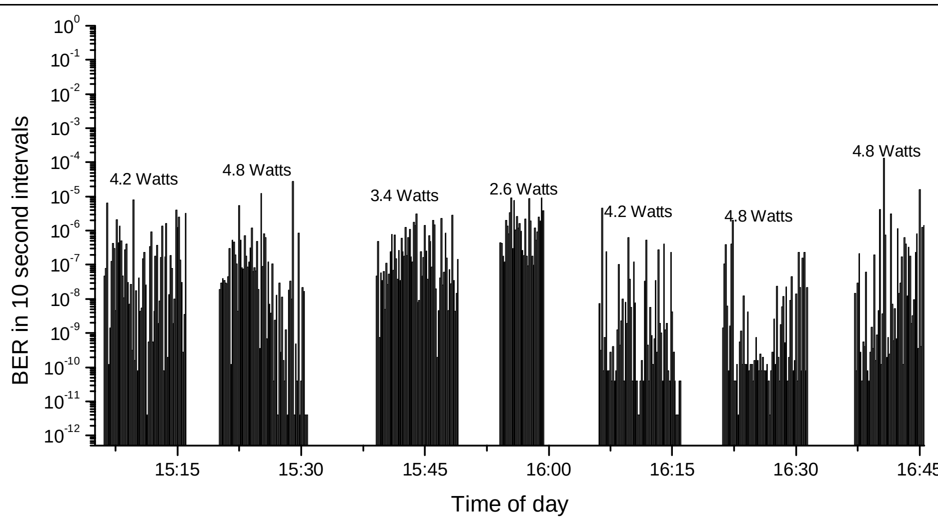

Figure 13: Results of BER testing on June 8tht 2005 using Novasol DMOI transceiver

During the testing, the transmitter power level was changed by up to a factor of approximately 2 as indicated over each grouping of data in Figure 13. The results show typical bit error rates between 10^{-11} and 10^{-5} with a slight trend toward higher bit error rates at lower transmitter power. Of most interest is the higher BER than observed with our standard lasercomm transceiver typically used at the LCTF (e.g., July 5th and 8th data shown above). This increase is partly due to the decreased aperture size of the Novasol receiver (D = 5") compared to the Meade telescope (D = 16") used in previous testing. This results in a raw received power reduction of approximately 10 dB and an increase in scintillation due to the reduction in aperture averaging. It is unclear if the reduction in aperture size is the sole reason for the reduction in BER performance over the standard lasercomm transceiver. More testing is required to determine if tracking, thermals through the open window, or some other effect are also contributing to the increased BER. Figure 14 shows the cumulative percentage of counts for measured BER below a fixed BER. Even with the increased BER over our standard transceiver, the performance of the system is respectable with a BER below 10^{-6} for 95% of the time.

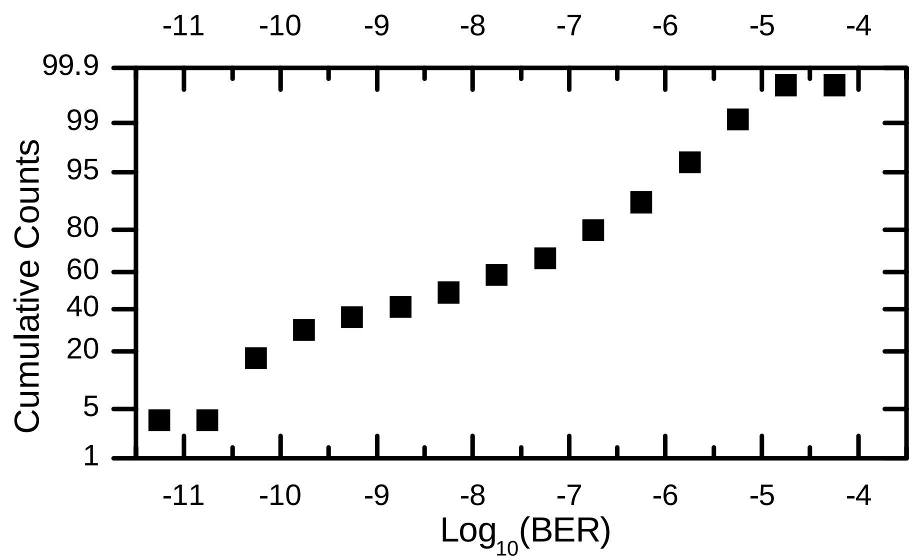

Figure 14: Cumulative probability of BER data shown in Figure 13

6. CONCLUSIONS

NRL has performed multiple lasercomm tests at NRL's 32 km folded path lasercomm test facility (LCTF). These tests have shown great promise for Naval lasercomm with successful data transmission at rates from 155 Mbps in light rain and fog to 2.5 Gbps in light haze and medium turbulence. NRL is currently in the process of upgrading the LCTF for long term operations over a direct 16 km path to assess lasercomm performance versus atmospheric conditions in a maritime environment. Construction of the upgraded test facility is ongoing and multiple tests have been performed to optimize the design and implement tracking for long term link closure at the facility. Operation of the one-way 16 km test facility will begin in the fall of 2005.

Testing of receivers optimized for free space lasercomm is being performed in parallel to construction of the upgraded test facility. Receivers optimized for maritime free space lasercomm will be integrated into the upgraded test bed and evaluated over the next several years. In particular, NRL has developed and field-tested a high-sensitivity (-33 to –34 dBm) OC-48 O-E-O converter with a multimode fiber input. This receiver has been used to close a 32 km lasercom link at bit rates up to 2.5 Gbps with both NRL's standard lasercomm transceiver and a commercial lasercomm transceiver developed by Novasol, Inc. Links at 2.5 Gbps were closed in a variety of atmospheric conditions from clear weather to heavy haze (vis < 10 km) to medium strength turbulence (C_n^2~$5x10^{-15}$).

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